Preprint

Semiconductor Modeling for Multi-layer, High Field, Photo-Switch using sub-bandgap Photons

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Abstract

High electric field geometries for high power, photo-conductive switches made possible by employing sub-bandgap photons and inter-bandgap dopants / defects are being investigated for compact pulse power systems. The high field, long absorption depth package reduces the required linear mode, optical closure energy and also reduces the conduction current density through the active material and at the contacts. In addition, the long absorption depth package increases the area available for thermal management and in concert with the reduced current density should increase the lifetime of the switch.

This paper describes the semi-conductor physics modeling of a multi-layer stack of GaAs wafers in a high electric field configuration. The model results of heavily doped n+ regions on electron injection, leakage current, and voltage hold off is discussed In addition, the modeling of the transverse injection of optical closure energy is discussed.

I.INTRODUCTION

The design of the high field strength photo-switch is a new approach that incorporates observations from a number of previous efforts. The new photo-switch configuration consists of a stack of multiple GaAs wafers in shown in figure 1. The layers are bonded together and to the top and bottom electrodes. Before bonding a high conductivity epi layer is deposited on both sides of each wafer and a metallic layer on the wafer under the electrodes. The electric field in the center of the switch is the largest and electric field at the edges has been reduced to assist in avoiding edge conduction.

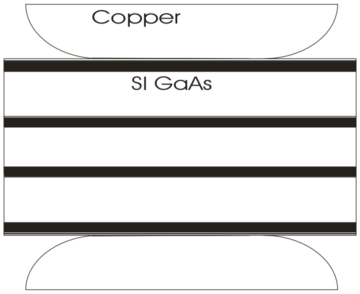

Figure1. Stacked layered Structure used for simulations 12mm length and 3- 350um thick wafers with epi layers 10um thick, curvature radius 2mm.

II. Device and Simulation

The switch consists of 3 stacked layers 350um each with a diameter of 1.2mm and depth of 0.8cm. The material is Liquid-encapsulated Czochralski (LEC) grown deep donor shallow acceptor (DDSA) GaAs where a balance is obtained between the deep lying EL2 and shallow acceptor impurity generally Carbon. The epi layers are 10µm thick where the dopant is generally Silicon (Si) with a concentration of $1e18/cm^3$. In the actual device Cu/Ti/Au/Ge/Ti have been used for the contacts. But in the simulations only Copper electrodes are considered. Simulations are performed on stacked layered structure starting with single 350µm layer and 1mm thick wafer. A prototype of these switches is being manufactured at Lawrence Livermore laboratories.

Atlas and Devedit modules of the Silvaco simulation code which provides two and three dimensional semiconductor device simulation were used in the present study. The Devedit module is used to fabricate the device. The Atlas module was interfaced with Blaze module to simulate III-V semiconductor devices. A large number of different physical models for mobility, recombination, and traps are available in the code. More information can be found in reference [3].

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III. Results and Discussion

The reasons for the breakdown of the photoconductive solid state switches PCSS) were unknown for many years. Latest research has shown a few improvements in our knowledge of the PCSS operation. The breakdown mechanism of the opposed contact PCSS is in the bulk [5]. The use of high conductivity epi layers at the electrodes to increase the breakdown strength of the photoconductive switch has already been shown. The epi layer at cathode helps in moving the high electric field from cathode into the bulk. It inhibits electron injection from the electrode until a higher bias is reached. As a result, there in no trap filled region next to the electrode and device breakdown does not occur till a much higher bias [1]. The epi layer at the anode helps in reducing current crowding thus improving the longevity of the switch [2].

The use of high conductivity epi layers helps not only in improving the breakdown strength of the switch but also helps in reducing the effect of surface breakdown. The simulations show a good response of the epi layer to reduction of surface electric field reducing the leakage current flow. Once these conditions are taken care of breakdown of the device depends solely on the material characteristics.

Following aspects are considered in the study:

1. Effect of epi layers on the breakdown and electron injection of the switches.
2. Effect of curved contacts on the switch performance
3. Effect of change in the trap density on the breakdown voltage.
4. Optical absorption depth with change in the trap density

The shape of the contact is changed from plane to curved profile. It has the beneficial effect of reducing the electric field at the triple point. We observed reduction of 20-50KV with the curved contacts over the plane contact case. When compared to New Mexico geometry circular contact remove the formation of CCNR for operating voltage ranges. This is shown in figure 2. Notice that the breakdown voltage of UMC switch is less than New Mexico geometry. The UMC device has 1mm length between the contacts as compared to New Mexico geometry which has 2.7mm length. This is the reason for low breakdown voltage.

The epi layer across the cathode helps in reducing the trap filled density near the cathode. So high electric field region is shifted from cathode to bulk GaAs. This also helps in inhibiting electron injection till high bias is reached [1]. The plot of structure with and without epi layers is as shown in figure 3. Similar result is obtained for stacked layered structure.

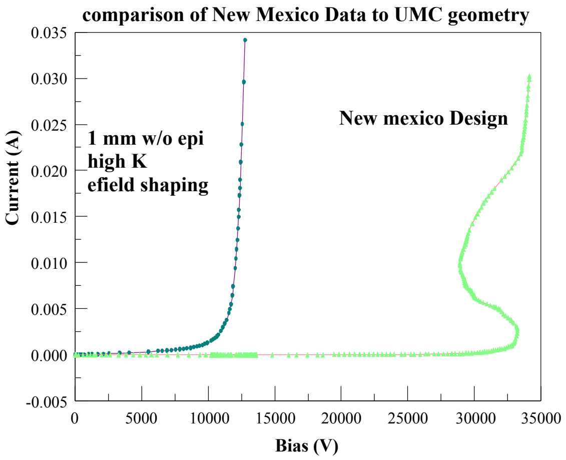


Figure 2. UMC and New Mexico geometry without epi layers

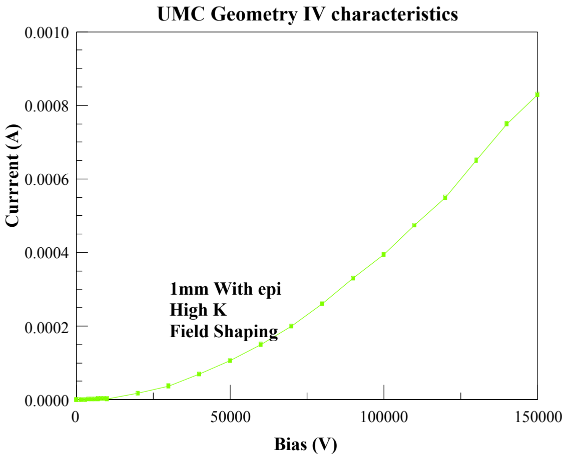


Figure 3. UMC geometry IV characteristics. Electron injection is inhibited till high bias.

The curved contact geometry is well tested with different radii of curvatures. The more the curvature, lesser the variation in the electric field. The curved contact should be perfectly smooth to increase breakdown voltage of the device. The point where the curved surface leaves the semiconductor is crucial as it directly affects the breakdown voltage of the switch. Once we get rid of bulk breakdown mechanism at contacts the impact ionization at high fields remains the reason for avalanche in these switches.

The trap density in the device is changed from $1e14/cm^3$ to $3e15/cm^3$. The change of this on the breakdown voltage is also considered. Figure 4 shows the effect of change in trap density on breakdown voltage at lower bias. As bias is increased towards breakdown, it changes the current controlled negative resistance as in figure 5. The main reason for current controlled negative resistance (CCNR) in these switches is impact ionization that occurs at high bias [1]. Increasing the trap density causes decrease in the impact rate so we get less CCNR.

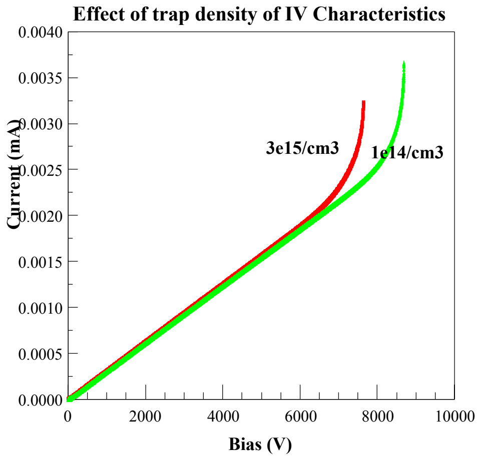


Figure 4. Effect of change in trap density at low fields.

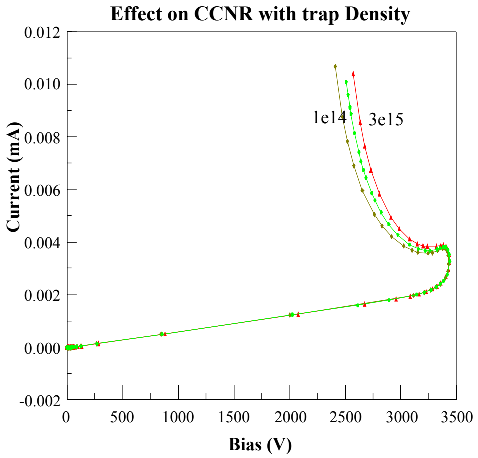


Figure 5. The trap density affects the CCNR of the switch at high fields

In the stacked case the IV plot looks as shown in figure 6. The breakdown voltage increases linearly with every layer added.

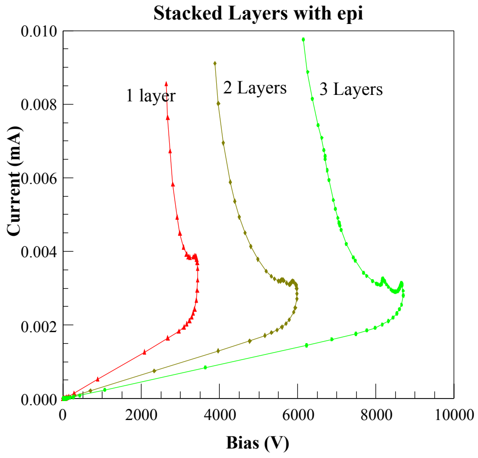


Figure 6. IV characteristics with 1-3 layers

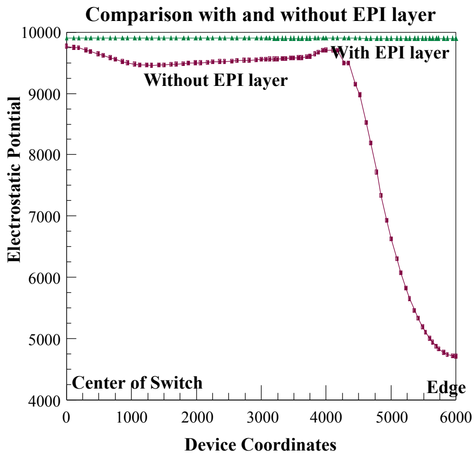
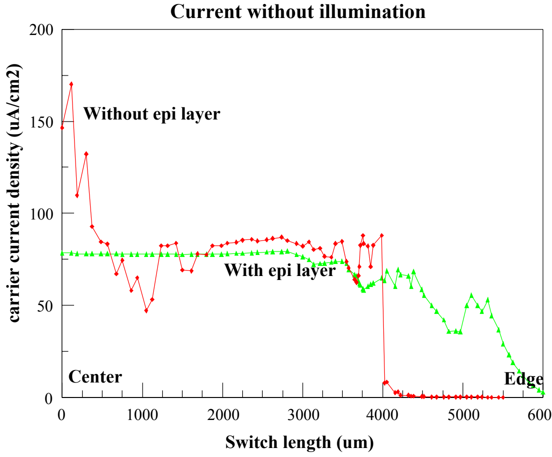


Figure 7. Effect of epi layer to on the electrostatic potential to the edge of wafer

Extension of the epi layers to the end of the device show less variation in the electrostatic potential towards the edges of the switch. This is as shown in figure 7. So to concentrate current in the middle of the switch a slight change is made in the length of the epi layer. The Epi layers are reduced just to cover contact length. This causes electrostatic potential reduced to zero at the edges avoiding current flow in edge regions.

IV. Transverse Injection of Optical Energy (1.06um)

Due to the limitation of the time required for the simulations and node points generated by mesh only half of the switch is simulated. The other half follows the same characteristics and is verified using a smaller device. The light of intensity 2e5 W/cm^2 is used. The current density in the device with and without illumination is as shown in figure 8. The fluctuation observed in 8b. are assumed to be computational noise.



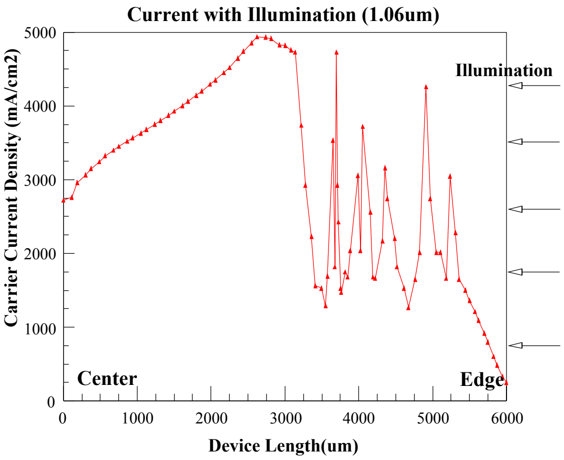


Figure 8. Plot of current flow in the switch with and without light for 5mm optical absorption depth.

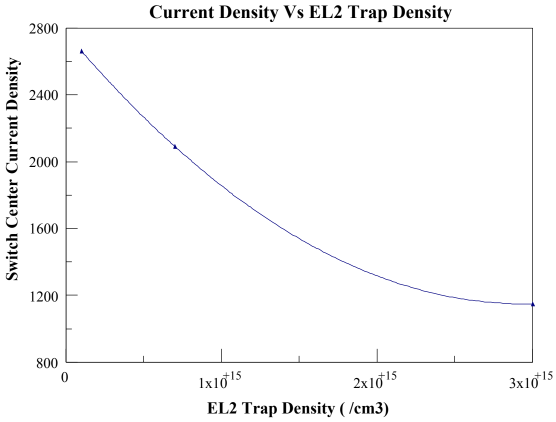


Figure 9. Current Density with D0=5mm inside the switch for different trap densities for stacked layer switch.

The density of the traps affect the carrier generation when illuminated. As the trap density increases more light is absorbed near the edges of the switch and thus the current in the middle of the switch decreases.

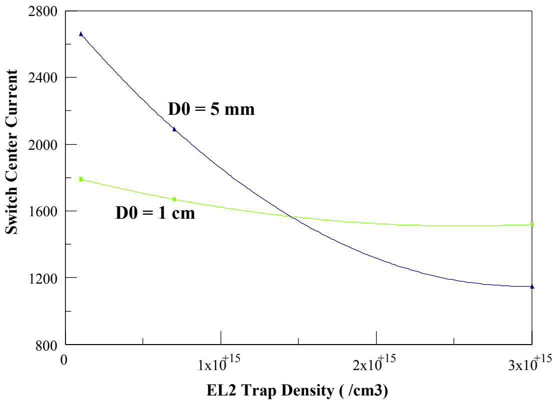


Figure 10. Effect of trap density on optical absorption depth.

In the case of 5mm optical absorption the current change is observed to decrease more with trap density as compared to the 1cm case. The carrier generation in 1cm case is seen to be constant throughout the switch. The middle layer carries more current. Similar is the case of electric field and occupancy. More states are occupied in the middle layer than the corner two.

V. Summary

We have discussed the advantages of the stacked layer structure with respect to Breakdown strength, electric field and electron injection. The shaping of the electric field reduces the probability of filamentation. The characteristics change in the carrier current is also discussed with illumination. The trap density plays a vital role in deciding the optical absorption in the switch. Ability to tailor the optical absorption depth enables the design of the switch that will enable us of the switch to any set of parameters allowed by physics of the material.

VI. References

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[5] N. E. Islam, E. Schamiloglu and C. B. Fleddermann "Analysis of high voltage operation of gallium arsenide photoconductive switches used in high power applications" Journal of Applied Physics Vol 86, nember3 august 1999.